Date: December 28, 2018

EIC Detector R&D Progress Report

Project ID: eRD17
Project Name: BeAGLE: A Tool to Refine Detector Requirements for eA Collisions
Period Reported: from July 2018 to December 2018
Project Leader: Mark D. Baker
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Abstract

As part of the EIC R&D program, the BeAGLE (Benchmark eA Generator for LEptoproduction) model code for simulating e+A collisions has evolved into a key element in the current efforts to refine the detector and interaction region design for both eRHIC and JLEIC, particularly in the forward region in the ion-going direction. As discussed in previous reports, there is a key physics measurement which is particularly demanding on the forward detector: identifying coherent diffractive events, where the nucleus remains intact, by vetoing those events where the nucleus is excited diffractively and emits particles. Because the conclusions from these and other e+A studies using BeAGLE may drive the forward detector/IR designs and possible tradeoffs, it is imperative that we use the best possible models and tune BeAGLE using our best information, as soon as possible.

To that end, we report on the progress and plans for extending BeAGLE by adding RAPGAP as an option in addition to PYTHIA to describe the hard e+N scatters (elastic or diffractive) which are part of the e+A collisions that need to be vetoed. We report on plans to validate BeAGLE's physics model (DIS + diffraction + nuclear effects) by tuning to the relevant E665 event-by-event μ+Xe streamer chamber data.

We also report on improvements made to the handling of e+D events in BeAGLE. This topic is hot right now in the DIS community and multiple groups approached us concerning this capability in BeAGLE. It was also discussed extensively at the recent INT workshop in 2018 (independent of BeAGLE). Light ions are particularly challenging to model and deuterons are not handled well in DPMJET,

so changes were needed. We also discuss briefly the plans, using external funding, to model short-range nucleon-nucleon correlations in BeAGLE.

Finally, we respond to the committee request from the July 2018 meeting: *"by the next meeting in January 2019 the committee would like to see a plan for accelerating the work, ensuring BeAGLE expertise is held more widely, and addressing continuity."* First, in order to accelerate the work, we include a supplemental proposal to cost-effectively increase the effort on this project. We propose to add 0.25-0.58 FTE years (student effort) through a modest increase in the travel budget. Second, we discuss the progress and plans for ensuring that BeAGLE is documented, widely accessible, version-controlled and maintainable, with a broad base of users and potential developers.

Past

Project History

When reviewing the history and progress of the eRD17 project, it is easy to get lost in the extensive tabulation of the detailed technical goals and achievements (Table 2 below). In this section, we will review the top level strategic goals.

As was discussed at the July 2018 meeting, EIC R&D Project 17 (eRD17), has expanded in scope since the initial proposal. We would like to emphasize that this was not really planned, but has been due to strong positive feedback from the committee and from the community. The BeAGLE model code has clearly filled an important need for exploring both the e+A physics potential at an EIC, and also the forward detector requirements for those measurements. This has led to pressure from the community for extensions to BeAGLE and validation of the results. This in turn resulted in, so far, one two-year extension of the original eRD17 proposal and two related, but independent, 2-year JLAB LDRD projects, one completed and one just starting. The LDRD projects will be covered in more detail in the "External Funding" section below.

Fiscal Year	BNL eRD17	JLAB LDRD
FY2016	DIS Shadowing year 1	
FY2017	DIS Shadowing year 2	Geometry Tagging year 1
FY2018	Add RAPGAP & Tune year 1	Geometry Tagging year 2
FY2019	Add RAPGAP & Tune year 2	Short-Range Correlations year 1
FY2020	?	Short-Range Correlations year 2 *

Table 1. Direct BeAGLE Project Support Sources by Fiscal Year

* - Proposed only. FY2020 funding decision will not occur until September 2019.

The original EIC R&D proposal was intended to be a one year project in FY2016 only. This project focused on DIS and the inclusion of multinucleon shadowing effects. Due to funding constraints, however, the committee stretched the project over two years (FY2016-2017) with the same total cost. This project achieved our primary original strategic goals by the end of FY2017: BeAGLE was released and available to use in improved geometry studies using forward detectors for both eRHIC & JLEIC. Studies at JLAB (mostly funded by the JLAB LDRD) [1] validated and extended previous eRHIC studies using DPMJET [2]. Further studies at BNL are ongoing.

Based on community and committee feedback on the importance of diffractive eA events and our discovery of how challenging it is to tag the breakup of the nucleus in these events, we proposed in June 2017 to increase the scope and extend the eRD17 project through FY2019. This will allow us to strengthen and validate BeAGLE's handling of diffractive (as opposed to DIS) events which may end up driving some of the forward detector & interaction region design decisions for e+A. Our target is still to complete this effort by the end of FY2019, as proposed, although the schedule is tight, as the committee noted at the last meeting. At the end of FY2019, then, BeAGLE should be well-tuned for both DIS and incoherent diffractive e+A (including unpolarized e+p), and along with Sar*t*re, this should give us a well-tuned complete suite of e+A event generators. Independently of the EIC R&D program, BeAGLE is also being upgraded to include known effects of Short-Range Nucleon-Nucleon Correlations (SRCs) which can lead to strong momentum correlations between the struck nucleon and one of the spectator nucleons of opposite isospin (i.e. struck proton and spectator neutron or vice versa).

Like the original proposal and the first (2-year) extension, any further proposed extensions of eRD17 are not intended to be automatic or incremental in nature, but will only occur if there is a clear need which is not being covered by other groups and which has significant bearing on clarifying the detector requirements for the EIC.

<u>What was planned for this period?</u>

As of the June 2018 written proposal, our plans were to finish the RAPGAP installation in BeAGLE, including implementing e+n collisions in RAPGAP, which currently only models e+p (items 19b-d in Table 2 below) by January 15, 2019. We also planned to update the BeAGLE documentation, merge all of the changes from the then two active developers, and release a consistent version at BNL and JLAB (item 21 below). We also planned to implement a process-dependent dipole cross-section, so that, for instance, J/psi diffractive and DIS events can, by default, have different and reasonable dipole cross-sections for Glauber multiple scattering (this would represent a partial completion of item 11c).

Between the June 2018 proposal and the July 2018 meeting, an opportunity presented itself. In a two week period, several groups asked us about running e+D collisions in BeAGLE for a variety of physics reasons, including:

- Spectator proton tagging to simulate e+n collisions in DIS and/or diffractive physics (with or without spin polarization).
- Full reconstruction of $e+D \to e'+p+n+J/\psi$ for low $|t|$ and high relative transverse momentum of the p and n in order to study the p+n interaction[3].
- Full reconstruction of $e+D \to e'+p+n+J/\psi$ as a reference sample for the study of short-range correlations (SRCs) in heavier nuclei using $e+A \to e'+(p+n)+J/\psi+X$ where (p+n) refers to back-to-back (in azimuth) nucleons.

In addition to expressing interest in the results, one group offered to collaborate to implement it correctly if needed. These collisions are of strong experimental and theoretical interest, but unfortunately DPMJET and BeAGLE are optimized for nucleons or heavy ions and don't handle light ions very well (more detail below). Based on the opportunity to handle this important physics topic and to train a talented new local BeAGLE developer, BNL Goldhaber fellow Zhoudunming (Kong) Tu, we added a plan to implement a more accurate distribution of nucleon momenta in the deuteron for e+D collisions in BeAGLE (item 22 below).

Finally, due to the increase in effort required to implement e+n in RAPGAP and e+D in BeAGLE, we abandoned our earlier plans to simulate Ultra-peripheral A+A collisions in BeAGLE in FY2019, although we are pursuing the possibility of finding external experts who can take this on with some support from us.

When this was presented at the July meeting, the committee expressed some concern about the large scope for this half-year as well as for the entire FY2019, even with the removal of the UPC effort, and suggested the possibility of increased manpower to expedite the project.

<u>What was achieved?</u>

The most important technical achievement since the last meeting was the merger of all versions of BeAGLE from the (now) three active developers into one release version and the establishment of a git repository to allow for more orderly parallel development. This version is available, and being used, at both JLAB and BNL as well as at the National Institute for Nuclear Physics and Particle Physics (IN2P3) in France and China University of Geosciences Wuhan (CUGW). The released version as well as some history is available in a served git repository, https://gitlab.in2p3.fr/BeAGLE/BeAGLE. The IN2P3 server allows users to login with their JLAB or BNL (or CERN or …) credentials and create a local account if needed. The repository has also been cloned at BNL as /afs/rhic.bnl.gov/eic/gitstore/BeAGLE and will be cloned at JLAB relatively soon. There continue to be up-to-date released builds at JLAB and BNL for general use. The use of git will make it much easier in the future to keep track of and merge the efforts of different developers, as we now have four developers (Mark Baker, Mathieu Ehrhart, Zhoudunming Tu and Liang Zheng). In addition, the documentation has been updated and improved at https://wiki.bnl.gov/eic/index.php/BeAGLE. Item 21 in Table 2 below can be considered settled. We in fact achieved more than was originally planned for this period on this topic. Clearly, it was a valuable investment in effort to make things more efficient in the future, to allow more people to work on the project effectively, and to ensure the long-term continuity of the project, but it took some time.

In general, the last five months have included a lot of discussion with the community, which was constructive but which also took some time and effort. In particular, Baker spoke on “SRCs @ EIC: Challenges in forward detection and simulation” at the CFNS workshop on Short-range Nuclear Correlations at BNL, Sept. 5-7, 2018 as well as on “MC Event Generator BeAGLE for Forward Physics at the EIC” at the CFNS workshop on Forward Physics and Instrumentation From Colliders to Cosmic Rays at Stony Brook University, October 17-19, 2018. This latter workshop allowed us to make contact with some of the authors and current maintainers of DPMJet as well as members of the Fluka collaboration which was particularly valuable. Unfortunately, we were unable to accept an invitation to talk at the Seattle INT Workshop "Probing Nucleons and Nuclei in High Energy Collisions" during the "eA Collisions" weeks Oct. 29-Nov.9, 2018 in Seattle, Washington.

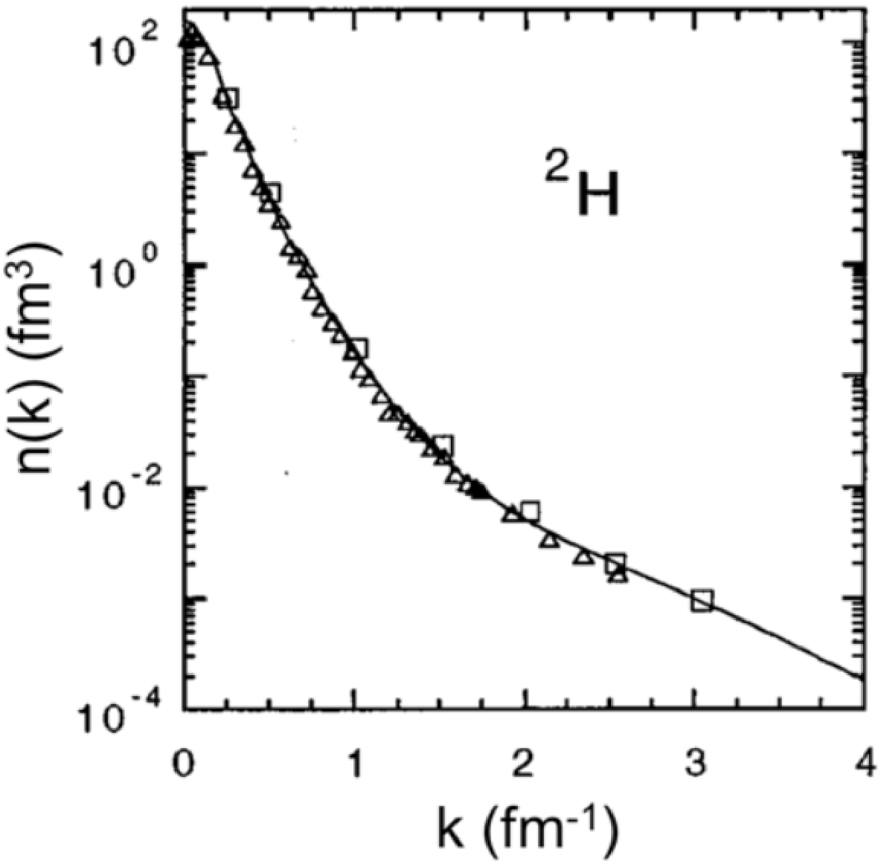

Figure 1. A "realistic" model for the nucleon momentum distribution n(k) ≡ dN/dk /(k^2) within the deuteron, where k is reported in units of (fm^{-1})≈197 MeV (natural units with ħ=1). Figure taken from Ref. [4,5]

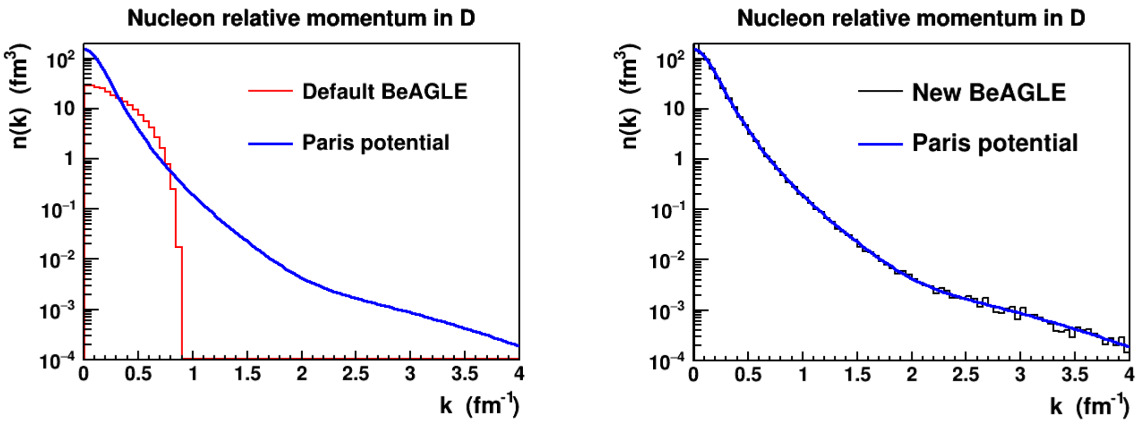

Figure 2. The nucleon momentum distribution n(k) for deuterons in BeAGLE compared to the functional form calculated using the Paris potential in Ref. [5], also plotted in Figure 1 of this status report. Left: Default BeAGLE distribution (from DPMJet). Right: New BeAGLE distribution. This figure was made in collaboration with Z. Tu.

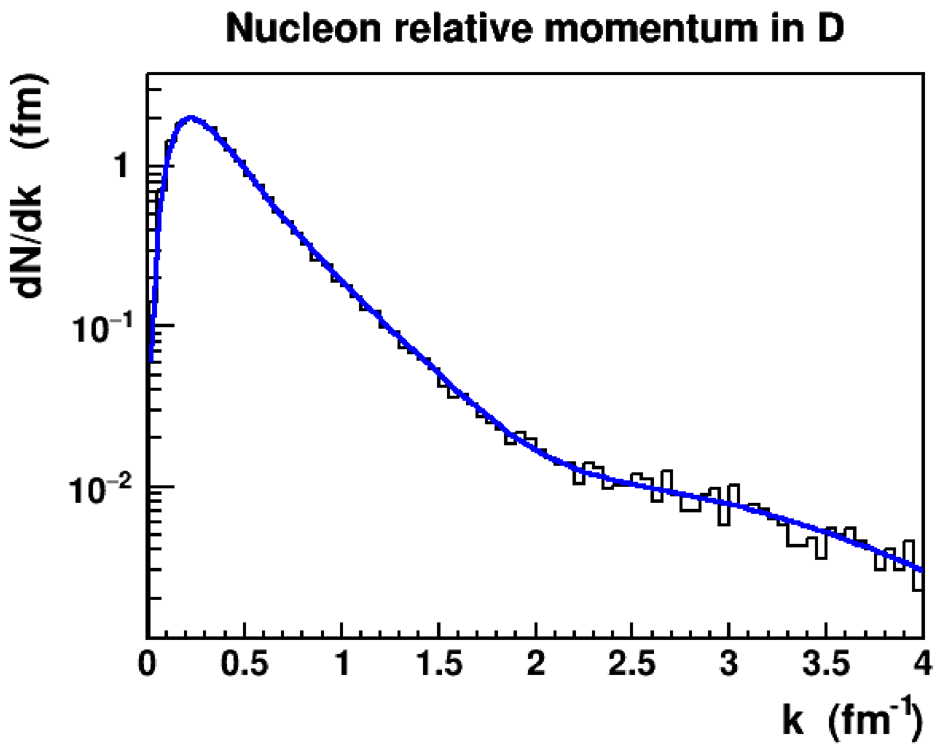

Figure 3. The nucleon momentum distribution dN/dk for deuterons in BeAGLE compared to the functional form calculated using the Paris potential in Ref. [5]. Note: $dN/dk = k^2\ n(k)$. This figure was made in collaboration with Z. Tu.

Another important project which was completed was to understand the deuteron implementation in BeAGLE (DPMJET), to review the modern understanding of deuterons and to improve the relative momentum distribution of the nucleons in the deuteron (item 22). This project was accomplished in collaboration with Zhoudunming “Kong” Tu from BNL with advice from JLAB experts: Christian Weiss (theory) and Douglas Higinbotham (experiment). Figure 1 shows the $n(k) \equiv \int d\Omega$

$(d^3N/dk^3) = (dN/dk)/k^2$ distribution from a realistic theory [4,5] where k is the momentum of one nucleon with respect to the center-of-mass (or half of the nucleon-nucleon relative momentum). Figure 2 shows the same distribution from BeAGLE. The left hand plot is the default distribution in BeAGLE (from DPMJet) which effectively treats the deuteron, inappropriately, like a large nucleus: a droplet of a Fermi liquid. The right hand plot shows the new distribution, taken from Ref.[5] which we installed in BeAGLE. These two distributions are significantly different, and it should be noted that there is a lot of physics interest in the region 1.5 < k < 4 fm^{-1} (0.3 GeV < k < 0.8 GeV). Studies done with DPMJET or the old version of BeAGLE will not properly reflect this important physics. It should also be noted that the tail is more important than it appears in the n(k) distribution where it is suppressed by the $1/k^2$ factor. Figure 3 shows the dN/dk distribution which reflects the actual frequency of k.

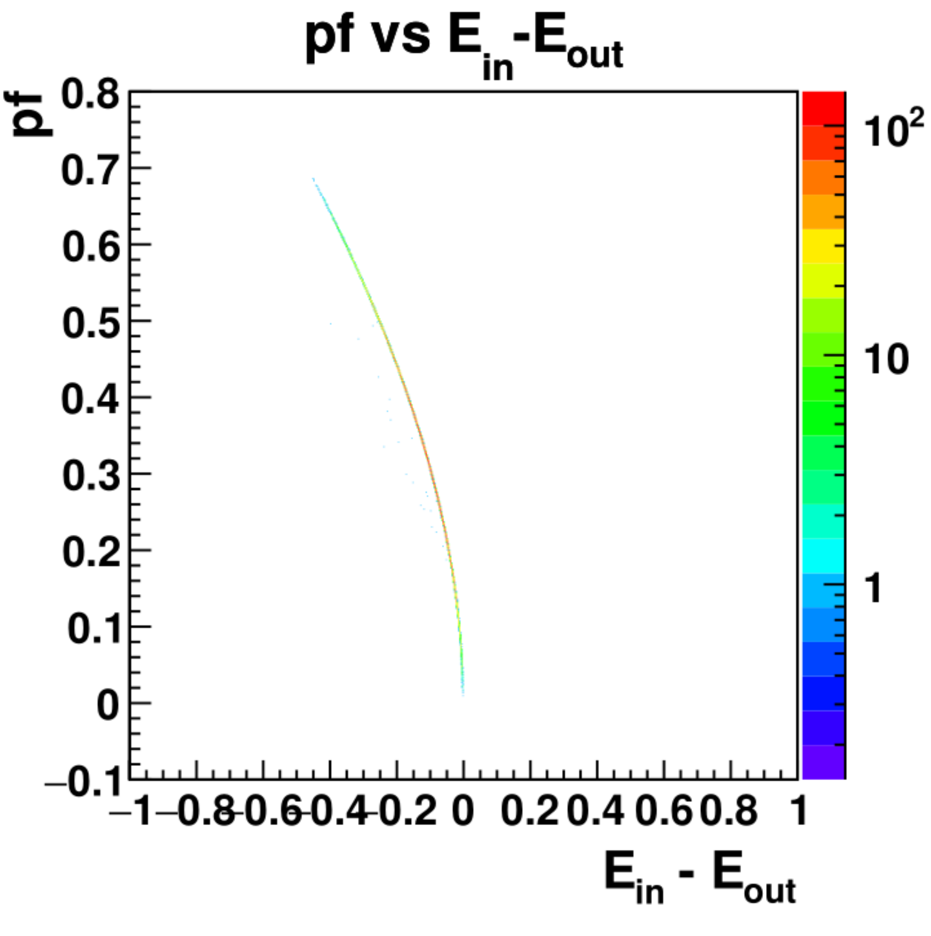

Figure 4. The correlation between k (labeled here as pf) and the energy non-conservation in the deuteron ion rest frame in the default version of BeAGLE (or in DPMJet). This figure was made in collaboration with Z. Tu.

As part of this effort, we discovered that there was an additional problem with how DPMJET handles deuterons which forced us to add a new “ToDo” item #23. Heavy nuclei are modeled in DPMJET & BeAGLE as a collection of free on-shell nucleons sitting in a mean field. After a collision, you typically have some e+N reaction products and an excited A-1 nuclear remnant. Nucleons leaving the nucleus interact with the mean field and lose energy. In addition, the nuclear remnant can take on a range of excitation energies, allowing 4-momentum to be conserved. The deuteron, in contrast, consists of two nucleons and after one is struck, the A-1 remnant is just a nucleon and has no mean field and no possibility of being an "excited nucleus". In another language, in the impulse approximation we think of the deuteron as approximately two free nucleons with momenta **k** and **−k**, but if we model it that way it will have too much energy in the deuteron rest frame: $E_{free} > M_p + M_n > M_D$. This problem is illustrated graphically in Figure 4, which shows the default results from BeAGLE and DPMJet. E_{in} refers to the energy of the incoming electron and deuteron in the deuteron rest frame while E_{out} refers to the energy of all final state reaction products in the same frame. As we increase "pf" or k, we increase the kinetic energy of the nucleons and the energy discrepancy increases in the rest frame of the incoming deuteron. In this frame, the 3-momentum is conserved correctly. Extrapolating the results to the (deuteron) mass shell is therefore the new task 23. So far, we were able to accomplish this with a uniquely defined, but completely ad hoc iterative adjustment of the outgoing particle momenta, allowing e+D in BeAGLE to conserve 4-momentum exactly.

After presenting these results, we learned in discussion with Christian Weiss of a more correct way to fix the final state 4-momentum, based on his understanding of the deuteron light-cone wavefunction. In frames with the γ^* and D momenta along the z-axis with the deuteron p_z non-positive and the photon p_z non-negative, you are allowed to adjust the p^+ light-cone variables of internal lines, while conserving p^-, p_x, p_y and keeping particles on mass-shell. Task 23 (on-mass-shell deuteron extrapolation) is therefore only partially finished, but understood.

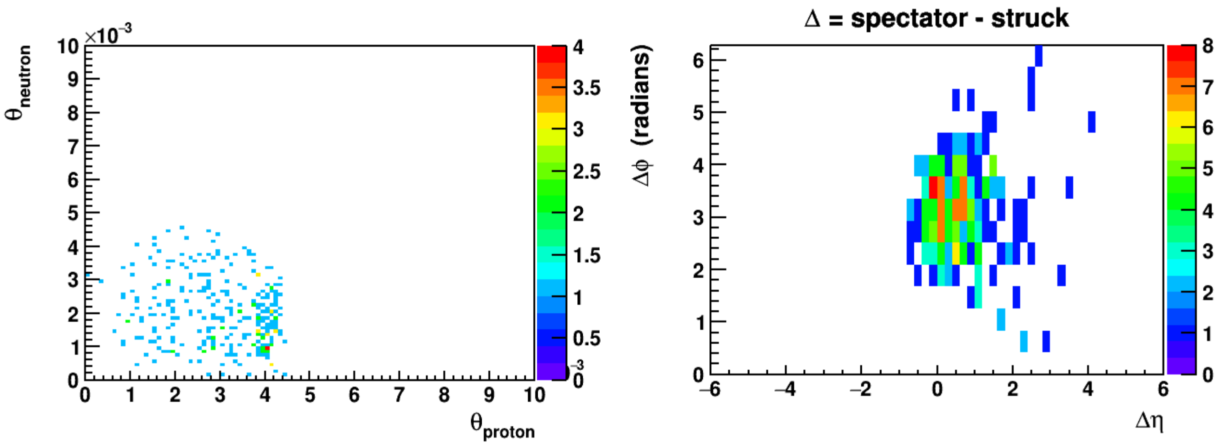

Figure 5. Correlation of proton and neutron angles for diffractive J/ψ–induced disintegration of the deuteron at full eRHIC energy for events with 550 MeV < k < 600 MeV and |t|<0.1 GeV^2. In these plots the neutron is the struck nucleon and the proton is the spectator. The left hand plot shows the neutron and proton polar angles with respect to the beam axis with axes ranging from from 0-10 mrad. The right hand plot shows the correlation in pseudorapidity and azimuthal angle of the spectator and struck nucleons. This figure was made in collaboration with Z. Tu.

Figure 5 shows an example of the kind of detailed study that is now available. It shows the process e+D→e'+p+n+J/ψ at full eRHIC energy. In these events a J/ψ is formed diffractively off of the neutron while breaking up the deuteron in the process, without breaking up the nucleons. This process will allow us to study the tails in the k distribution as well as the pn interaction. In addition it will serve as reference data for the study of short-range correlations in heavier nuclei. We have selected a narrow bin in the nucleon momentum k inside the deuteron and examined the acceptance and correlation. The cut on $|t|<0.1$ GeV^2 is necessary in order to keep the struck neutron in the acceptance. At higher values of |t| the neutron angle gets larger. The right hand plot shows that the nucleons emerge back-to-back ($\Delta\phi \approx \pi$), allowing them to be tagged.

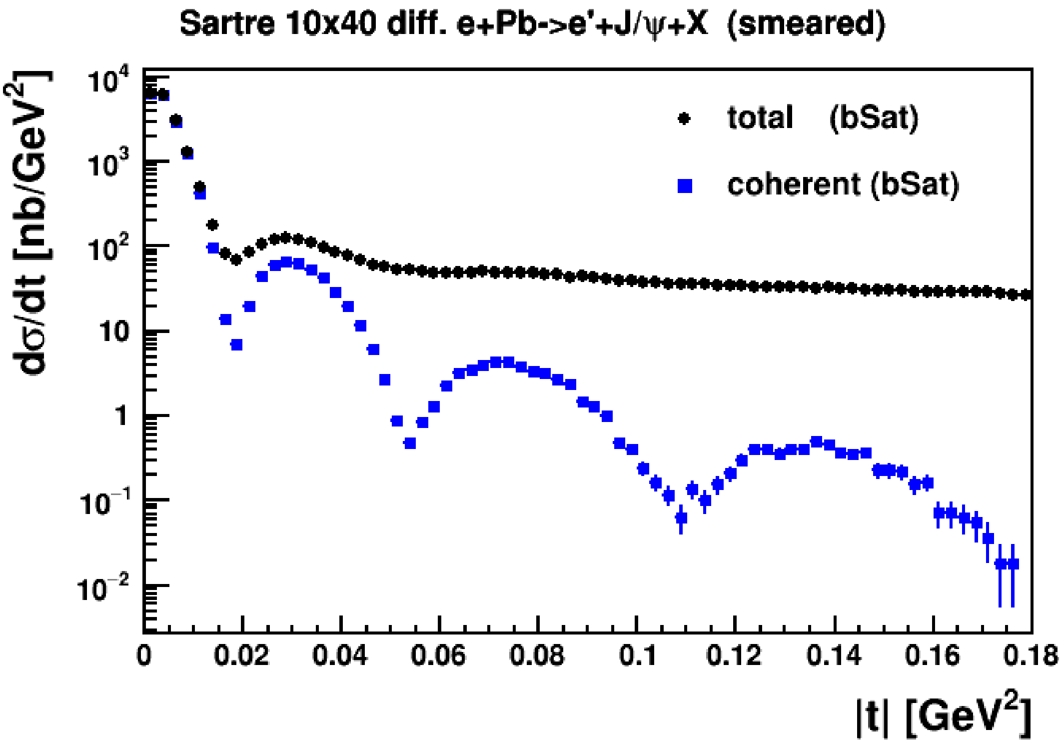

Figure 6. Simulated data from Sar*t*re for diffractive e+Pb→e'+J/ψ+X for 10x40 GeV with 5% relative smearing in t. The square blue points are the coherent data while the circular black points are the total distribution if we do not veto-tag the incoherent data. Results generated in collaboration with the JLAB Geometry Tagging LDRD collaboration (V. Morozov et al.).

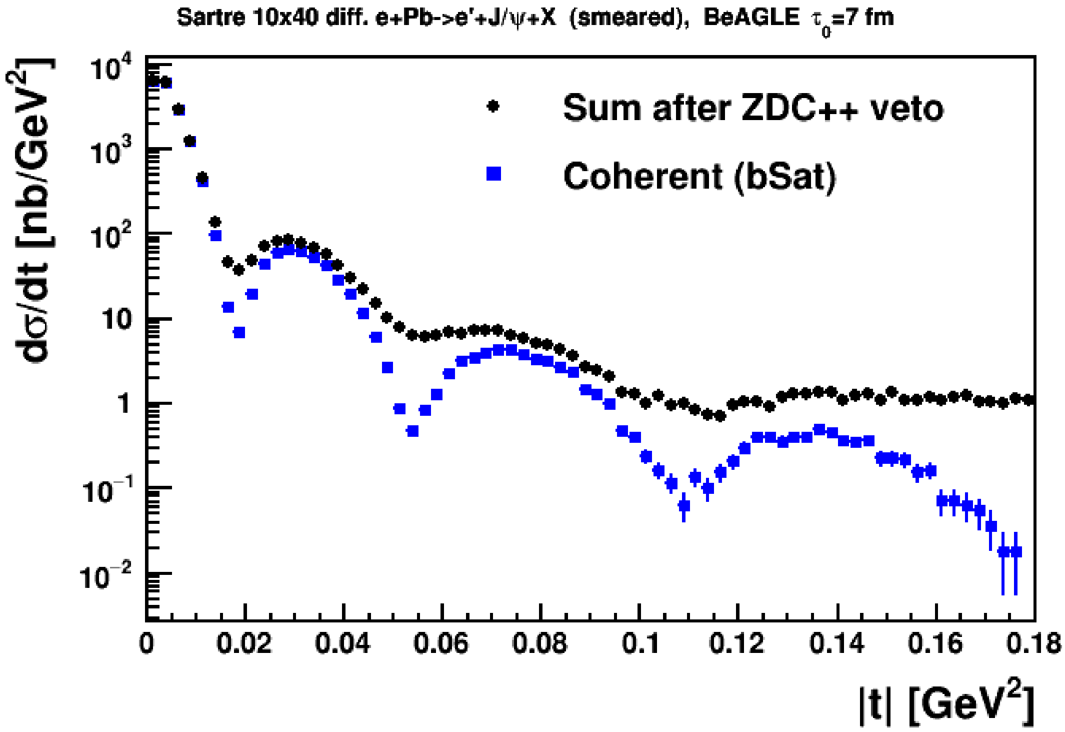

Figure 7. The square blue points are again simulated Sar*t*re coherent data e+Pb→e'+Pb+J/ψ for 10x40 GeV with 5% relative smearing in t. The circular black points show the effect of "ZDC++" veto-tagging simulated for the JLEIC detector (see text). Results generated in collaboration with the JLAB Geometry Tagging LDRD collaboration (V. Morozov et al.).

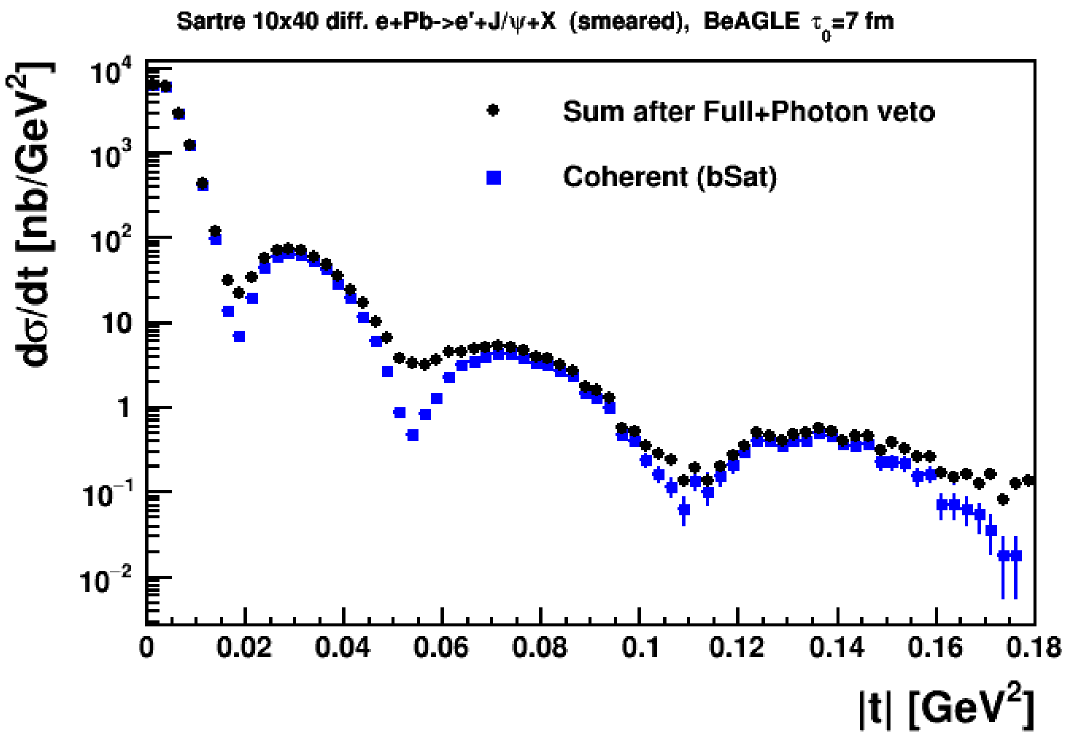

Figure 8. The square blue points are again simulated Sar*t*re coherent data e+Pb→e'+Pb+J/ψ for 10x40 GeV with 5% relative smearing in t. The circular black

represent the impact of the "Full+photon" veto-tagging simulated for the JLEIC detector (see text). Results generated in collaboration with the JLAB Geometry Tagging LDRD collaboration (V. Morozov et al.).

Figures 6-8 show the latest information about our ability to extract coherent diffractive events by vetoing the incoherent events. Recall that the diffractive J/ψ production process e+Pb→e'+J/ψ+X consists of coherent events where the Pb nucleus remains intact and unexcited as well as incoherent events where the nucleus emits particles: nucleons, pions, photons etc.. The coherent events contain information about the spatial distribution of gluons in the Pb nucleus. The incoherent events contain valuable information about the fluctuations of the spatial distribution, but they also serve as a large background for the coherent data. Vetoing this background is one of the more challenging tasks which may well drive decisions about the forward detector and interaction region designs.

In all three figures, the blue points represent simulated data from Sar*t*re for coherent diffractive e+Pb→e'+Pb+J/ψ for 10x40 GeV with 5% relative smearing in t. In Figure 6, the black points represent all diffractive e+Pb→e'+J/ψ+X data from Sar*t*re: both incoherent and coherent. It is clear from Figure 6 that tagging is needed. Figure 7 shows the effect of veto-tagging using "very forward" particles at JLEIC. The black points were generated using dσ/dt from Sar*t*re and assuming the "ZDC++" veto-tag efficiency from a BeAGLE+GEMC simulation for the JLEIC detector. Note: GEMC is the JLAB GEant Monte Carlo. Events are vetoed if they have a forward neutron in the ZDC, a forward photon in the ZDC with energy > 40 MeV, or a forward charged particle which survives the Final Focusing Quadrupoles (approximately $\theta<10$ mrad). Figure 8 is similar to Figure 7, except that the black points represent the effect of tagging using "forward" particles rather than "far forward". Events are vetoed if they have a forward particle which makes it through the first dipole aperture (approximately $\theta<20$ mrad): neutron, charged particle or photon with energy > 40 MeV. This is called "Full+Photon veto". It should be noted that in Figures 7-8, events were also vetoed if they had a produced hadron or high-energy photon ($E_\gamma>500$ MeV) in the main detector ($\theta>100$ mrad), but this main detector cut rejects very few events. This physics relies on the forward detector.

Clearly the veto efficiency is strongly affected by our acceptance for forward particles. The JLAB Geometry Tagging collaboration has started to look into the impact of this veto efficiency on the reconstruction of the input G(b). Preliminary results are encouraging. The black and blue points in Figure 8 seem to result in the same reconstructed G(b) even thought the black points are not a perfect reconstruction. We cannot yet confirm that it is the same as the input G(b) because these plots use a preliminary hybrid set of Sartre cross-section tables which are actually a mix of Au and Pb tables. Final results will have to await the ongoing regeneration of the full Pb Sar*t*re tables where the input G(b) will be understood.

Because this important physics appears to be very challenging for forward detection, it may drive design decisions and tradeoffs in the IR design. It is therefore essential that we tune and validate BeAGLE as well as possible as soon as possible.

To this end, a critical task for this time period was further integrating RAPGAP into BeAGLE (items 19b-c) and extending RAPGAP to include e+n as well as e+p collisions (item 19d). This task started late, but is proceeding well. A β release (item 19b) exists. Due to the late start, a full release (19c) by the time of the January 2019

EIC R&D meeting is possible, but time is tight. Upgrading RAPGAP to include e+n (19d) will likely slip by a couple of months, but we have not seen any particular difficulties or showstoppers in the integration. RAPGAP uses PYTHIA particle common blocks and even some subroutines, so the integration is much easier than it would be with a completely independent code.

Feature added or error corrected	07/2018	12/2018	Planned
1-8. Early BeAGLE features (see previous reports).	YES	YES	YES
9. Shadowing coherence length	NO	NO	YES
10. Partial shadowing effect	YES	YES	YES
11a. Effective σ_{dipole} for J/ψ averaged over x & Q^2	YES	YES	YES
11b. Effective σ_{dipole} for ϕ averaged over x & Q^2	YES	YES	YES
11c. Eff. $\sigma_{dipole}(x,Q^2)$ for $V=\psi,\phi,\rho,\omega$ from Sartre (ePb)	NO	NO	YES
11d. Use correct $R_{diff}^{(A=208)}(x,Q^2)$ for V from Sartre	NO	NO	YES
11e. Improved σ_{dipole} for V, if necessary	NO	NO	YES
12. Tune to E665 μA Streamer Chamber data	NO	NO	YES
13. FS p_F for hard process correct	YES	YES	YES
14. Kinematic matching between DPMJet&Pythia	YES	YES	YES
15. Protect against very high E* values.	YES	YES	YES
16. Enable nPDF with any value of A,Z (EPS09)	YES	YES	YES
17. Extend $R\rightarrow\sigma_{dipole}$ map to more values of A	YES	YES	YES
18. Tune the t distribution for multiple scattering.	NO	NO	YES
19a. Release α version BeAGLE/RAPGAP	YES	YES	YES
19b. Release β version BeAGLE/RAPGAP	NO	YES	YES
19c. Release tested version BeAGLE/RAPGAP	NO	NO	YES
19d. Extend RAPGAP to include e+n (w/ H. Jung)	NO	NO	YES
20. Allow diffraction w/ individual $V=\psi,\phi,\rho,\omega$	YES	YES	YES
21. Cleanup and document BeAGLE work so far.	NO	YES	YES
22. Update Fermi momentum distributions for e+D.	NO	YES	YES
23. Put e+D on mass-shell (light-cone prescription)	NO	Ad-hoc	YES
XX. Implement UltraPeripheral Photon Flux	NO	NO	NO
XX. Tune BeAGLE to UPC data (RHIC &/or LHC)	NO	NO	NO

Table 2. Technical accomplishments and plans through FY2019.

Table 2 contains the summary list of goals and accomplishments. As discussed above, we accomplished items 19b, 21 and 22 as planned, exceeding our plans in item 21. In addition, we added a new item 23 and achieved a practical, but not theoretically ideal, success on item 23. We expect to be able to address the planned "Process-dependence of dipole cross-section" by January 2019 R&D Meeting (part of 11c).

What was not achieved, why not, and what will be done to correct?

As we discussed above, item 19d has slipped, probably by about two months to mid-March rather than the planned mid-January. This is due primarily to the investments we made in fixing e+D and installing BeAGLE in git, all of which took more effort than expected. Fixing the deuteron in BeAGLE represents a significant and topical increase in our ability to understand whether the forward detectors are adequate for detecting the tails in the deuteron k distribution. A simple back of the envelope calculation shows that a neutron with p_T=500 MeV and p_z=110 GeV is at the edge of the eRHIC ZDC, pushing the limits of our detectors. Detailed studies, including forward proton acceptance, will be needed to understand the detector requirements. Putting BeAGLE in git was a valuable investment in effort in the short-term to make things more efficient in the future, to allow more people to work on the project effectively, and to ensure the continuity of the project.

In order to respond to this slip and also expand the base of people developing and supporting BeAGLE, as suggested by the committee, we have investigated the possibility of using a modest infusion of additional funding to increase the effort. The solution that we found was to support Central China Normal University PhD student Wan Chang's housing (dorm room) and per diem expenses at BNL for 5 months at a cost of $24,000. This is detailed below in the Supplemental Proposal Section.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

The next six months should see the main results of the two year FY2018-2019 effort starting to become available, with final results by the end of the fiscal year. The goal, by October, is to have a fully working BeAGLE with both Pythia and Rapgap available, which is tuned to the available target-region e+A & μ+A data. This should improve the ongoing efforts at BNL and JLAB to use BeAGLE in detector/IR optimization and give us more confidence in any conclusions.

We are planning to finish all of the items from Table 2 by the end of the fiscal year.

Item 9, “shadowing coherence length” has been repeatedly postponed because it is not very important for many of the studies so far which have focused on small x ($x<0.002$) or on the valence region. E665 data, however, includes a substantial amount of data in the transition region $0.01<x<0.1$ where the coherence length could be important.

Items 11c-d are further improvements to the diffractive dipole (rescattering) cross-section and the overall eA/eN diffractive cross-section ratio. These are also important for the comparison of E665 data with RAPGAP-enabled BeAGLE. Item 11c refers to a plan to use the Sartre results to infer the correct dipole cross-section for multiple scattering for each vector meson as a function of Q^2 and x rather than just matching the value averaged over Q^2 and x. Item 11d refers to making sure that the overall diffractive cross-section ratio between ePb and eN matches that of Sartre. Finally, item 11e recognizes that a better formalism may be needed to relate Sartre $\sigma(eA)/\sigma(eN)$ behavior to the rescattering probability in BeAGLE, especially for the

ϕ,ρ,ω mesons where the suppression due to gluon saturation is strong and therefore the inferred rescattering cross-section is large.

Line 12 refers to comparing BeAGLE+Sartre to the E665 Streamer Chamber data once BeAGLE handling of diffraction has been improved. This is really one of the main thrusts of the entire project.

Line 18 refers to a small improvements to the BeAGLE model for the effect of shadowing. Currently, the scale of the soft multiple scattering is given by the intrinsic k_T of the parton in the nucleon. For the diffraction case, this scale should be given by the t distribution of the elastic component of incoherent diffraction.

Line 19 is self-explanatory: the installation of RAPGAP into BeAGLE, along with testing and release of the final code. This, along with item 12, represents the major thrust of this project.

Line 23 represents a small improvement in the on-mass-shell extrapolation of the e+D interaction as described in more detail above. The theoretically optimal approach was not obvious, but we now know how to handle it and it should be relatively straightforward.

<u>What are critical issues?</u>

We do not foresee any major difficulties with the implementation of the BeAGLE upgrades. The main open-ended issue is how well BeAGLE will match the data when the upgrades are finished and how much tuning will be needed if there are significant discrepancies. The schedule is tight, but may be achievable even without additional funded effort. Adding Chang to the project, though, should speed things up, decrease the chances of a major delay, and improve our understanding of the sensitivity of BeAGLE conclusions to the tuning parameters. Making the data comparisons (Chang) in parallel to the BeAGLE upgrades (Baker) will allow us to prioritize the upgrades more wisely during the year, since it may become clear sooner which issues are more urgent.

<u>Additional information – response to committee's charge:</u>

There has been substantial discussion throughout this report in response to the committee's charge: "*Since BeAGLE is essential to establishing the EIC detector requirements, by the next meeting in January 2019 the committee would like to see a plan for accelerating the work, ensuring BeAGLE expertise is held more widely, and addressing continuity.*" We summarize our response here.

First of all, with regard to "*accelerating the work*", we would like to repeat the exchange in the homework session of the July meeting.

<u>Committee:</u> *If more money would be available could you hire or pay someone to accelerate the completion of your to-do-list?*

<u>Baker:</u> Yes. With additional funds, it should be possible to get things done a little faster and reduce the risk of a delay due to unforeseen problems.

<u>Committee:</u> Do you have someone specific in mind?

Baker: Yes. (In fact we had Wan Chang in mind already in July, but it quickly became clear that funding would not be available immediately at that time, so this discussion was postponed until now).

The follow-up to all of this is that Wan Chang (CCNU/BNL) is available now, is familiar with running and analyzing BeAGLE, and would be able to start immediately. Her salary is covered by her home institution and she is already resident at BNL. We would only need to cover her expenses at BNL. Our supplemental proposal is detailed below.

With regard to the issue of *"ensuring BeAGLE expertise is held more widely",* we took the advice from the committee as motivation to actually ensure that BeAGLE expertise is held more widely, rather than just planning for it! We have already made great progress in this regard. The establishment of a git repository makes it practical for more people to be involved efficiently. There are now four people, at four different institutions, who have actively modified BeAGLE and can be considered potential developers: Mark Baker (MDBPADS), Mathieu Ehrhart(IN2P3), Zhoudunming "Kong" Tu (BNL), and Liang Zheng(CUGW), with Baker and Zheng as BeAGLE experts. An even broader base of people who know how to run BeAGLE exists and it is in use in at least four places: BNL, JLAB, IN2P3 & CUGW. Having Wan Chang work intensively with BeAGLE for the next half year can only improve this situation.

In terms of *"addressing continuity",* BeAGLE has already achieved escape velocity and can be meaningfully used without any one individual being completely essential. There is also substantial community expertise in Pythia (including Aschenauer, Diefenthaler…) and in DPMJet (e.g. Aschenauer, Lee, Zheng) which can translate into understanding BeAGLE. It should be noted that DPMJET-F (DPMJet with Fluka), at the heart of BeAGLE, was written by Nestor Armesto, also a member of the EIC community. We continue to engage and train students and postdocs and even more senior scientists to spread the knowledge.

Of course, having said this, Baker is unavoidably central to the project, due to a unique confluence of work history, skills, and interests. Postdocs and students can act as force-multipliers, but there needs to be someone with a comprehensive and deep interest in and knowledge of the model. BeAGLE is rather complicated, involving the stitching together of multiple other programs. Other senior physicists (including now Zheng) are too busy to go that deep and postdocs and students turn over too fast. Further, in the U.S. it is difficult for a young scientist to get recognition for contributing to phenomenology and model-building as their main activity, so there is a limit to the amount of effort that they can put into it. The maintenance of BeAGLE and especially timely upgrading of the code with new physics abilities would be difficult without Baker, and that is hard to avoid. Even down the road, if other models come on-line, Baker will be able to use BeAGLE as a benchmark to ensure that important physics isn't missing from those other models. In fact, the interaction with the Sar*t*re effort has already proven the value of BeAGLE in this regard.

Fortunately, Baker is available for the foreseeable future as long as funding remains available. It would probably be optimal in the long run to have a multi-year contract between MDBPADS and one or more institutions, rather than proceeding indefinitely on a year-by-year and project-by-project basis.

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

Baker is the only funded person on the project, working one-quarter time (0.25 FTE) on average. The FY2018 money was fully spent. Spending on FY2019 is expected to begin soon, but so far, none has been spent as officially no work occurred in October or November 2018.

Supplemental Proposal

We propose to support Central China Normal University PhD student Wan Chang's housing (dorm room) and per diem expenses at BNL for 5 months. Ms. Chang is already resident at BNL, but focused on other tasks than BeAGLE-tuning. The availability of Wan provides an excellent opportunity. She already has some familiarity with running and analyzing BeAGLE, and is plugged in with the BNL EIC group, with Elke Aschenauer as her local advisor.

If we bring Chang on board, she would be able to run BeAGLE under a variety of conditions, comparing it to the various target-region data that we want to match: E665 event-by-event streamer chamber μ+Xe data, E665 event-averaged μ+Pb and μ+Ca neutron data, and the ZEUS forward proton and neutron data. BeAGLE has already been tuned to the E665 neutron data and ZEUS forward data, but we'll want to continue to match that data while ensuring that we can describe the event-by-event E665 charged particle (streamer chamber) data. Having her work on this will free Baker up to focus more on the technical upgrades to BeAGLE and it will speed up the work of tuning BeAGLE allowing us to get a basic result more quickly and do a more thorough job of exploring the parameter space and the sensitivity of the BeAGLE output to the tuning parameters.

Fully loaded expenses for staying at BNL add up to about $4800/month. The minimum practical additional effort is 3 months, due to start-up inefficiency. The maximum effort available is 7 months (March – September, 2019), assuming that it takes until March to get the funding.

Effort Level	Additional Funding	Comments
3 FTE months = 0.25 FTE years	$14,400	Minimum practical
5 FTE months = 0.42 FTE years	$24,000	PROPOSED
7 FTE months = 0.58 FTE years	$33,600	Maximum practical

This funding is in addition to the already approved funding for FY2019 which covers 0.25 FTE-year for Baker and 1 month of travel support (airfare + local BNL expenses) for Zheng.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

Brookhaven National Laboratory Physics Department funding supported the salary of Aschenauer and Lee who have primarily been working in an advisory role. Similarly, China University of Geosciences (Wuhan) supports Liang Zheng's salary.

The JLAB LDRD "Geometry Tagging for Heavy Ions at JLEIC" (FY2017-2018) project was completed. Vasiliy Morozov (JLAB) was the P.I. and collaborators included: A. Accardi, M.D. Baker, W. Brooks, R. Dupre, M. Erhardt, K. Hafidi, C. Hyde, P. Nadel-Turonski, K. Park, A. Sy, T. Toll, G. Wei, L. Zheng. Some collaborators from that project have continued working on BeAGLE and forward detector issues. In particular, Vasiliy Morozov (JLAB) is working on updating Sar*t*re tables while Raphaël Dupré (IPN-Orsay) and his student Mathieu Ehrhart are upgrading PyQM (optional partonic radiative quenching model) in BeAGLE as well as taking the lead on establishing version control in BeAGLE using git. Tobias Toll (Indian Institute of Technology, Delhi) is working on inverting the results to recover G(b).

Baker and Zheng are now participating in a new JLAB LDRD planned for FY2019-2020: "Tagged Short-Range Correlations For Medium To Heavy Ions at JLEIC", which includes an upgrade of the BeAGLE nuclear model to allow the possibility for quasi-deuterons as well as independent neutrons and protons inside of the nucleus. This effort will be independent of the effort on eRD17, but will also contribute to our understanding of EIC physics capabilities and forward detector requirements. Collaborators, in addition to Baker and Zheng include: Or Hen (MIT), Florian Hauenstein(ODU), Douglas Higinbotham (JLAB – PI), Charles Hyde (ODU), Vasiliy Morozov (JLAB), and Pawel Nadel-Turonski (SBU). Additional collaborators from BNL and SBU are planning to join this effort as well.

BNL provided funding in FY2018 for BNL Goldhaber Fellow Zhoudunming "Kong" Tu, who also contributed to eRD17, implementing the correct data-driven distribution of relative ("Fermi") momentum of the nucleons in a deuteron (item 22 in Table 2), in collaboration with Baker, as well as collaborating on other issues concerning e+D (such as item 23 in table 2).

Publications

Please provide a list of publications coming out of the R&D effort.

None so far.

Conclusion

Bibliography

[1] V. Morozov et al., "Geometry tagging for heavy ions at JLEIC", Proc. 26th Intl. Workshop on Deep Inelastic Scattering and Related Subjects (DIS2018), Kobe, Japan, April 16-20,2018 , published in PoS DIS2018 (2018) 175.
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[3] G. Miller, M. Sievert, R Venugopalan, "Probing short-range nucleon-nucleon interactions with an Electron-Ion Collider", Phys. Rev. C 93 (2016) 045202.
[4] O. Hen, G. Miller, E. Piasetzky, L. Weinstein, "Nucleon-nucleon Correlations, Short-lived Excitations, and the Quarks Within", Rev. Mod. Phys. **89** (2017) 045002.
[5] C. Ciofi degli Atti, S. Simula, "Realistic model of the nucleon spectral function in few and many nucleon systems", Phys. Rev. **C53** (1996) 1689.